



University of Southern Queensland
Faculty of Engineering & Surveying

Modelling of Electrokinetic Phenomena in Soils

By

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Abstract

The aim of this work was to develop theoretical methods for the prediction of remediation time and the electrical energy requirements for the remediation of soil contaminated with sodium chloride. Laboratory scale experiments were specially designed and performed on sand and clay samples at field capacity moisture content to identify the key features of electrokinetic processes in soil. The experiments confirmed the existence of a prominent ionic concentration or conductivity front travelling away from the cathode. The dissertation offers a novel theoretical explanation that links this front to the electronegative charge bound onto soil particles. A mathematical model of electromigration in soil is developed based on that theory. The model is essentially a set of partial differential equations (PDEs) with some coefficients behaving non-linearly. An algorithm for numerical solution of the PDEs is developed using a finite difference time domain approach. Reasonable agreement was found between laboratory test results and prediction of the corresponding numerical models. In addition, approximate analytical solutions to the PDEs allow remediation time and remediation energy requirements to be evaluated. The results of this work may be generalised to soils with ionic contamination other than sodium chloride.

*Dedicated to
My very unique mother,
My dear father, and siblings,
My wife and children (Shaima, Sharafalden, Sufyan and Abdelmalek)*

Certification of Dissertation

I certify that the ideas, experimental work, results, analysis, software and conclusion reported in this dissertation are entirely my own effort expect where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any other award, except where otherwise acknowledge.

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Contents

Abstract.....	i
Acknowledgments.....	iv
List of Figures	x
List of Tables.....	xiv
List of symbols and abbreviations.....	xv
Chapter 1: Introduction	1
1.1 Project justification.....	1
1.2 First order estimation.....	4
1.3 Aim and objectives	8
1.4 Organisation of the thesis	9
1.5 Summary of outcomes.....	10
Chapter 2: Literature Review	11
2.1 Introduction	11
2.2 Transport processes	13
2.3 Principle of electrokinetic soil remediation.....	15
2.4 Electroosmosis.....	16
2.4.1 Electroosmosis theory	19
2.4.2 Electroosmosis permeability coefficient	19

2.4.3	Hydraulic gradient and matric suction development during electroosmosis	22
2.5	Electromigration	27
2.5.1	Electromigration theory	28
2.6	Electrophoresis	31
2.7	Diffusion	32
2.8	Electrochemical reaction	33
2.9	Factors affecting electrokinetic processes	35
2.9.1	Electrode type	35
2.9.2	Applied voltage	38
2.9.3	Electrical conductivity of soils	39
2.10	Coupling phenomena	40
2.11	Summary	46
	Chapter 3: One-Dimensional Laboratory Tests	48
3.1	Introduction	48
3.2	General explanation of tests performed	48
3.2.1	Electrokinetic cell setup	48
3.2.2	Soil preparation	50
3.2.3	Soil analysis methods	50
3.3	Tests results	51
3.4	Key findings from experimental work	72

3.5	Explanation for formation of concentration fronts during electrokinetic treatment.....	78
3.5.1	Cation exchange capacity of soils	78
3.5.2	Proposed theory.....	79
3.5.3	Limitations of the proposed theory	84
3.6	Summary	86
	Chapter 4: Model Development and validation	88
4.1	The electrical equation and its solution	88
4.2	The set of electromigration equations	93
4.3	Determination of mobilities and initial ionic concentrations	97
4.4	Initial and boundary conditions	102
4.5	Discretisation of the electromigration equations.....	105
4.6	Validation of the proposed theory	108
4.7	Summary	110
	Chapter 5: 2-D and 3-D Modelling of Electromigration.....	112
5.1	2-D and 3-D modelling.....	112
5.2	Two-dimensional validation test	119
5.3	Influence of the anode	123
5.4	Generalised analytical expression for remediation time and remediation energy requirements.....	124
	Chapter 6 Conclusions and Further work.....	128
6.1	Conclusions	128

6.2	Further work	130
	References	131
	Appendix	137

List of Figures

Figure 1.1: Simplified decontamination process.....	5
Figure 1.2: Salt accumulation around root zone drip irrigated plants.....	7
Figure 1.3: Targeted remediation area	7
Figure 2.1: Distributions of cations and anions adjacent to clay surface (Mitchell, 1993)	14
Figure 2.2: Principle of electroosmosis through soil (Probstein, 1989).....	17
Figure 2.3: Variation of electroosmosis permeability with pH value	22
Figure 2.4: Variation of pore water pressures for one-dimensional electroosmosis with given boundary conditions	26
Figure 2.5: Electromigration of ions (adapted from (Acar et al., 1994)).....	27
Figure 2.6: Electrophoresis phenomenon in soils	32
Figure 2.7: Na concentration profiles during electrokinetic treatment	44
Figure 3.1: Electrokinetic set-up (a) sketch of electrokinetic experiment set-up (b) soil column sections and (c) anode and cathode segments	49
Figure 3.2(a): Voltage variations across different soil sections during electrokinetic treatment.....	54
Figure 3.2(b): Current variations during electrokinetic process	54
Figure 3.2(c): Sodium ion distribution in soil-water sampled at suction points during electrokinetic treatment.....	55
Figure 3.2(d): Sodium ion distribution in soil column before and after electrokinetic treatment.....	55
Figure 3.2(e): Variation of electrical conductivity (EC) in soil column before and after electrokinetic treatment.....	56

Figure 3.2(f): Variation of pH in soil columns before and after electrokinetic treatment.....	56
Figure 3.2(g): Variation of soil moisture content before and after electrokinetic treatment.....	57
Figure 3.3(a): Voltage distribution across different soil sections during electrokinetic treatment.....	58
Figure 3.3(b): Voltage and current waveforms during electrokinetic treatment.....	58
Figure 3.3(c): Sodium ion distribution in soil-water sampled at suction points during electrokinetic treatment.....	59
Figure 3.3(d): Sodium ion distribution in soil column before and after electrokinetic treatment.....	59
Figure 3.3(e): Variation of electrical conductivity (EC) in soil column before and after electrokinetic treatment.....	60
Figure 3.3(f): Variation of pH in soil columns before and after electrokinetic treatment.....	60
Figure 3.3(g): Variation of soil moisture content before and after electrokinetic treatment.....	61
Figure 3.4(a): Voltage distribution across different soil sections during electrokinetic treatment.....	62
Figure 3.4(b): Total voltage variation with time during electrokinetic treatment.....	63
Figure 3.4(c): Sodium ion distribution in soil column before and after electrokinetic treatment.....	63
Figure 3.4(d): Variation of electrical conductivity (EC) in soil column before and after electrokinetic treatment.....	64

Figure 3.4(e): Variation of pH in soil columns before and after electrokinetic treatment.....	64
Figure 3.4(f): Variation of soil moisture content before and after electrokinetic treatment.....	65
Figure 3.5(a): Voltage distribution across different soil sections during electrokinetic treatment.....	66
Figure 3.5(b): Voltage and current waveforms during electrokinetic treatment.....	67
Figure 3.5(c): Sodium ion distribution in soil column before and after electrokinetic treatment.....	67
Figure 3.5(d): Variation of electrical conductivity (EC) in soil column before and after electrokinetic treatment.....	68
Figure 3.5(e): Variation of pH in soil columns before and after electrokinetic treatment.....	68
Figure 3.5(f): Chlorine ion distribution in soil column before and after electrokinetic treatment.....	69
Figure 3.5(g): Variation of soil moisture content before and after electrokinetic treatment.....	69
Figure 3.6: Electrokinetic setup with cathode chamber design.....	70
Figure 3.7(a): Variation of electrical conductivity (EC) in soil column before and after electrokinetic treatment.....	71
Figure 3.7(b): Variation of pH in soil columns before and after electrokinetic treatment.....	71
Figure 3.8: Conductivity or ionic concentration regions	72
Figure 3.9: Idealised voltage (V_{xy}) across middle segment of soil column.....	74
Figure 3.10: Conductivity at point x	75

Figure 3.11: Sodium concentration profile	75
Figure 3.12: The depletion surface	83
Figure 4.1: One-dimensional model.....	89
Figure 4.2: One-dimensional representation of equation 4.15	95
Figure 4.3: One-dimensional representation of equation 4.16	95
Figure 4.4: Effective mobilities.....	99
Figure 4.5: Anionic and cationic currents	100
Figure 4.6: Flow chart for numerical solution of electromigration equations	107
Figure 4.7: Comparison between measured and calculated voltage profiles	109
Figure 4.8: Effect of the choice of anionic to cationic current ratio for $K = (0.2$ and $0.8)$	110
Figure 5.1: Resistance branches between nodes in 2-D geometry (conductances due to cations and anions combined into a single branch)	114
Figure 5.2: Resistance branches between nodes in 3-D geometry (conductances due to cations and anions combined into a single branch)	114
Figure 5.3: flow chart for numerical solution of the one, two or three-dimensional discretized electromigration equation	118
Figure 5.4: Two-dimensional validation test (a) Photograph of the setup (b) Positions of the voltage probes	120
Figure 5.5: Voltage profiles used to identify the position of the concentration front	121
Figure 5.6: Comparison of concentration front movement.....	122
Figure 5.7: Effect of Anode size on the speed and shape of the concentration front	123

List of Tables

Table 2.1: Coefficients of electroosmosis permeability	21
Table 2.2: Electrode materials and voltage transfer	37
Table 3.1: Key finding from experiments	76
Table 4.1: Effect of choice of anionic to cationic current on remediation energy...	109
Table 5.1: Theoretical resistance of basic earthing electrodes	127

List of symbols and abbreviations

A	Cross-sectional area of soil tube (m^2)
C	Concentration of ions in (mol/l) or (C/m^3)
CEC	Cation exchange capacity
C_i	Concentration of species i (moles/ m^3)
C_h	Pre-treatment ionic concentration (C/m^3)
D	Dielectric constant of the pore fluid (F/m)
D^*	Diffusion coefficient (m^2/s)
D_{eff}	Effective diffusion coefficient in soil (m^2/s)
dr	Incremental distance normal to depletion surface (m)
dt	Incremental time (s)
E	Electric field gradient (V/m)
EC	Electrical conductivity (S/m)
F	Faraday constant (C/ mol)
GN_i	Soil conductance due to negative ionic species (S)
GP_i	Soil conductance due to positive ionic species (S)
H^+	Hydrogen ion
H	Hydraulic head gradient

I	Current through soil column (A)
I_{nd}	Anionic current in the depletion region (A)
I_{nh}	Anionic current in high conductivity region (A)
I_{pd}	Cationic current in the depletion region (A)
I_{ph}	Cationic current in the high conductivity region (A)
J	Current density (A/m ²)
J_d	Ion flux due to diffusion (mol /m ² . s)
J_i	Total Flow rate of specific ion (mol /m ² .s)
J_m	Migration flux of salt ions (mol /m ² .s)
J_n	Anionic contribution to current density (A/m ²)
J_p	Cationic contribution to current density (A/m ²)
I_s	Electrode injected current (A)
K	Anionic to cationic current ratio within the high conductivity region
K_e	Coefficient of electroosmosis permeability (m ² /V.s)
K_h	Hydraulic conductivity (m/s)
K_n	Average anionic mobility (m ² /V.s)
K_p	Average cationic mobility (m ² /V.s)

List of symbols

K_{pr}	Pressure permeability coefficient ($\text{m}^2/\text{Pa.s}$)
L	Length of soil tube (m)
L_{ac}	Anode to cathode distance (m)
OH^-	Hydroxyl ion
PDEs	Partial differential equations
Q_w	Electroosmosis flow rate (m^3/s)
R	Universal gas constant (J /K mol)
RN_i	Branch resistance representing electrical current carried by negative ions (Ω)
RP_i	Branch resistance representing electrical current carried by positive ions (Ω)
r	Radius of depletion surface (m)
R_{ac}	Total anode to cathode resistance (Ohm)
S	Speed of the depletion surface (m/s)
T	Absolute temperature (K)
V	Total applied voltage (V)
V_a	Anode potential (V)
V_c	Cathode potential (V)
W	Remediation energy (Watt)
v_h	Seepage velocity due to hydraulic gradient (m/s)
Z	Charge number

Z_b	Length of depleted region (m)
ε	Soil electrical permittivity ($C^2/N.m^2$)
ζ	Zeta potential (V)
η	Viscosity of the pore fluid ($N.s/m^2$)
μ	Mobility of ions in the electrolyte solution ($m^2/V.s$)
μ_{eff}	Effective mobility of ion in soil ($m^2/V.s$)
ρ	Electrical resistivity (Ωm)
σ	Soil electrical conductivity (S/m)
σ_d	Soil conductivity in depletion region (S/m)
σ_h	Per-treatment soil conductivity (S/m)
σ_{ni}	Partial conductivity of soil at node i due to anion electromigration (S/m)
σ_{pi}	Partial conductivity of soil at node i due to cation electromigration (S/m)
σ_m	Minimum soil conductivity (S/m)
τ	The soil tortuosity
φ	Soil porosity
∇p	Pressure gradient (Pa/m)
Δt	Time interval (s)
ϕ	Electrical potential (V)